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Cogging-free actuator based on printed circuit boards

Paul Binder[1], Tillmann Volz[1]

[1]*Physik Instrumente SE & Co.KG*

P.Binder@pi.de

Abstract
The demand for highly dynamic, direct-driven, compact positioning systems continues to grow. However, conventional electromagnetic drives are not always sufficient. They often have high torque ripple, which has a negative effect on positioning accuracy. The choice of different manufacturers is also limited to a small selection of motors that are suitable for such applications. For this reason, Physik Instrumente (PI) SE & Co. KG has developed a semi-rotary actuator based on multilayer printed circuit boards. This design allows the actuator to be easily scaled to meet any requirements. The principle of the axial flux machine is used for this purpose. This has the advantage of high modularity based on a stacked structure. In this case, additional PCBs can easily be added to increase the torque of the actuator. To ensure high dynamics, a moving-coil approach was chosen, which is easily possible due to the semi-rotary design. However, to cover a working area as large as possible, the principle of a 3-phase motor has been followed. This means that it is easy to increase the angle of movement by using a larger magnet array. To ensure precise positioning, a distributed 3-phase concept without an iron core was chosen, which minimizes torque ripple. Due to the variably changeable conductor track width, it was possible to integrate a very small winding head into the circuit board. The concept was tested for its thermal behaviour and precise positioning using a functional model. The paper presents various measurements of the functional model.
Accuracy, Actuator, Hexapod, Ultra-precision

1. Introduction

Direct driven six degree of freedom parallel kinematic machines (PKM) for sub-micrometer positioning are seen as promising candidates for a variety of alignment applications like wafer level testing and packaging in silicon photonics or optical assembly tasks, like e.g. lens alignment in LIDAR sensors. However, deploying direct-driven PKMs on an industrial scale requires the systems to have a long lifespan, extended maintenance intervals, a compact size, and low costs, all while maintaining very high precision and sufficient payload capacity . Primarily, costs, precision, size, integrability and payload are decisively influenced by the drives used in a PKM [1]. Consequently, Physik Instrumente (PI) developed a technology demonstrator of a three-phase electromagnetic motor based on pie-shaped stacked PCB coils without iron cores, that aims primarily on reduced costs and positionability while offering a good integrability and sufficient torque. On one hand, PCB coils can be produced in large quantities at very low cost, while on the other hand, their shape allows for excellent integration, especially in PKMs with base-point motion of struts along a circular path when no full rotation of the motor is necessary. In addition, the stacked coil approach enables good scalability of torque by changing the number of used coils in an actuator or scaling the size and length of the printed circuit board tracks in the PCB coils.

2. Actuator Design

This chapter provides an in-depth description of the mechanical and electrical design aspects of the rotational actuator, which are necessary to enable high-precision roational positioning.

2.1. Mechanical Design

The actuator was designed with five stacked individual PCB coils connected in parallel as shown in figure 1 (coils marked by ①). The coils are attached to a polymere coil holder (marked by ② in figure 1) which isolates the shaft from the PCBs thermically to prevent severe temperature elongation of the shaft (marked by ④ in figure 1) and as a result a change in bearing preload. The chosen bearings (marked by ③ in figure 1) are high precision angular ball bearings. The bearings are axially preloaded to prevent any play in radial and axial direction.

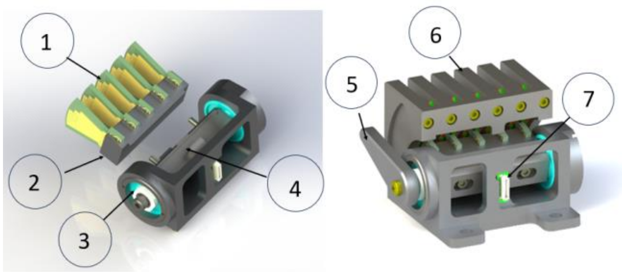

Figure 1. Structure of the actuator with pie-shaped stacked PCB coils

A portion of the shaft consists of a hub, which has the encoder scale on its outer surface. The scale is used together with an optical incremental encoder readhead (marked by ⑦ in figure 1). On one end of the shaft, the lever (marked ⑤ in figure 1) with a length of 45 mm and an interface for applying load is attached. The PCB coils are located between the magnet holders (marked ⑥ in figure 1). For maximum torque, Halbach-arrays are used in the actuator. The gap between coils and magnets is 0.5 mm. Both, the coil holder and the magnet holders can be moved laterally to align the coils and magnets precisely.
Since Halbach-arrays are used, the coil holder can be made from polymer for example 3D-printed.

Dependent on desired load, motion range, resolution and dynamics (velocity and acceleration), the length of the lever, the encoder scale diameter and the number of PCB coils can be adapted.

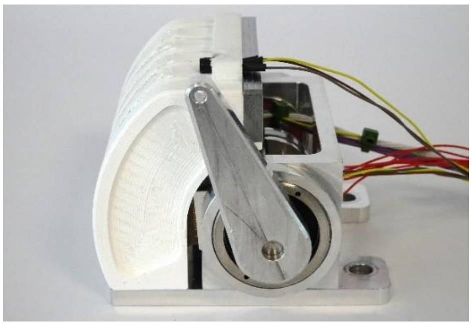

Figure 2. Full assembly of the actuator

The resulting specifications of the actuator as described above are shown in the following table.

Table 1 Specifications of the stacked PCB coil actuator

Number of stacked PCBs	5
Maximum force with 45 mm lever length	4 N
Maximus torque	180 mNm
Maximum current	5 A
Postion resolution (along the encoder scale)	~ 1.7 nm

2.2. PCB Design

The PCB consists of 18 layers with a copper layer thickness of 70 µm (figure 3). There are four windings per layer. However, in order to realise the winding head, two layers must always be routed parallel, resulting in a total winding number of 36 turns per coil. Due to the various possibilities offered by printed circuit boards, a winding head can be realised in a small space. The properties of the coils can be changed quickly and easily using automated routing.

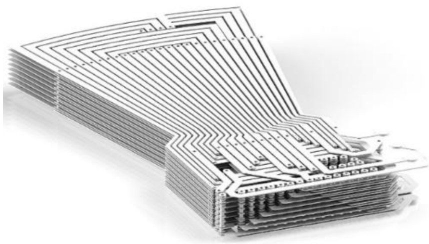

Figure 3. Copper layers of the PCB coil

3. Qualification

Under different loads, the temperature of the coils was recorded and the corresponding torque to current ratio was measured. The results are shown in table 2.

Table 2 Measurements of the stacked PCB coil actuator

Force/N (45 mm)	Torque/mNm	Current/A	Temperature/°C after 1 hour
1	45	1.69	28.75
2	90	2.85	38.25
3	135	4.16	58.25
4	180	5.15	71.00

At approx. 5 A (maximum current of used drivers), the temperature of 71°C is still acceptable for the PCBs.

To determine the smallest steps the actuator can perform (resolution) minimal incremental motion (MIM) tests were carried out. The result in figure 4 shows very good 50 nm steps which makes the actuator suitable for a use in e.g. high precision alingnment PKMs.

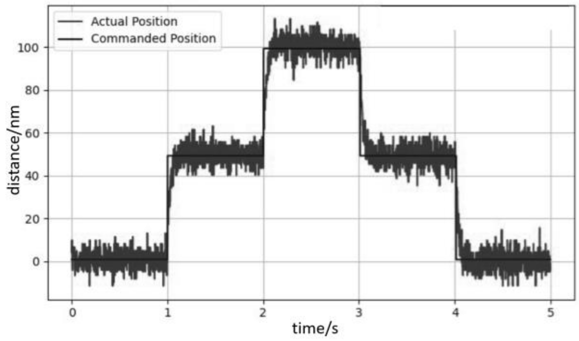

Figure 4. MIM with a step size of 50 nm (15 mm lever length)

Regarding the interconnection of coils, the difference between parallel and serial was analysed. Here, the coil stack was connected in series, which leads to improved positionability, as the coils have a higher inductance and lower currents, at the expense of performance (torque).

For a first characterization of the dynamic performance of the actuator, which is an important specification in many alignment applications, various sinusoidal motions were performed by the actuator. Figure 5 shows an oscillation of 30 Hz with an amplitude of 500 µm. This corresponds to an acceleration of approx. 18000 mm/s². Tests were also carried out with an acceleration of 36000 mm/s², whereby a slight phase shift and overshoot were observed. Again, these first results meet the requirements for actuators used in positioning systems very good.

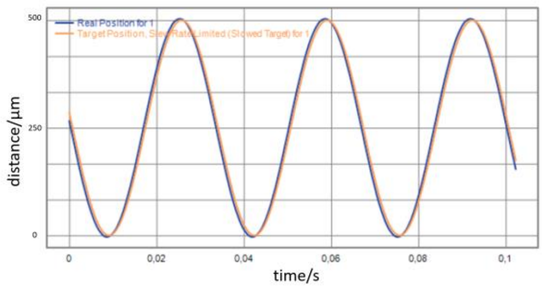

Figure 5. Sinusoidal trajectorie at 30 Hz and 500 µm amplitude

4. Conclusion and Outlook

The qualified actuator has shown very promising results regarding resolution and dynamics. However, an optminzation of the PCB coils is evident, mainly to increase the torque by increasing the copper fill factor and an optimization of current flow to reduce power losses. All in all, the actuator concept offers a very good opportunity to build a high-precision positioner that can be easily adapted to both mechanical and electrical requirements. The special shape of the actuator can also be used, for example, to build a compact PKM in which the actuators are combined with each other.

References

[1] Matitschka J. et al. 2023 Air bearing hexapod for motion and positioning in six degrees of freedom with sub-micrometer precision, Proc. Of the 18th Int. Conf. of the euspen